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document The light baryon spectrum in a relativistic quark model with instanton-induced quark forces The non-strange baryon spectrum and ground-states Ulrich Löringe-mail: loering@itkp.uni-bonn.de, Bernard Ch. Metsch Herbert R. Petry Institut für Theoretische Kernphysik, Universität Bonn, Nußallee 14–16, D–53115 Bonn, Germany U. Löring *et al.*

This is the second of a series of three papers treating light baryon resonances up to 3 GeV within a relativistically covariant quark model based on the three-fermion Bethe-Salpeter equation with instantaneous two- and three-body forces. In this paper we apply the covariant Salpeter framework (which we developed in the first paper Loe01a) to specific quark model calculations. Quark confinement is realized by a linearly rising three-body string potential with appropriate spinorial structures in Dirac-space. To describe the hyperfine structure of the baryon spectrum we adopt 't Hooft's residual interaction based on QCD-instanton effects and demonstrate that the alternative one-gluon-exchange is disfavored phenomenological grounds. Our fully relativistic framework allows to investigate the effects of the full Dirac structures of residual and confinement forces on the structure of the mass spectrum. In the present paper we present a detailed analysis of the complete non-strange baryon spectrum and show that several prominent features of the nucleon spectrum such as *e.g.* the Roper resonance and approximate "parity doublets" can be uniformly explained due to a specific interplay of relativistic effects, the confinement potential and 't Hooft's force. The results for the spectrum of strange baryons will be discussed in a subsequent paper Loe01c. 11.10.StBound and unstable states; Bethe-Salpeter equations12.39.KiRelativistic quark model12.40.YxHadron mass models and calculations14.20.-cBaryons Introduction intro In the previous paper Loe01a we analyzed the three-fermion Bethe-Salpeter equation with instantaneous two- and three-body interaction kernels. Without being too specific concerning the interaction kernels, we derived the three-fermion Salpeter equation. We now want to apply this covariant formalism to a system of three light quarks with flavors up, down and strange and thus use this fully relativistic framework as basis for a quark model of light baryons. In fact, the reduced Salpeter equation provides a suitable, fully relativistic framework, which nonetheless keeps as close as possible to the rather successful non-relativistic potential models: On the one hand, we found a one-to-one correspondence of the Salpeter amplitudes with the ordinary states of the non-relativistic quark model meditated by the embedding map of non-relativistic three-quark Pauli spinors to full three-quark Dirac spinors. On the other hand, this approach adopts the concept of constituent quarks with an effective mass where the underlying interactions are described by inter-quark potentials in the rest-frame of the baryons. Hence, we basically have the same input describing the quark dynamics as in non-relativistic quark models, in particular the number of parameters remains exactly the same as in a corresponding non-relativistic approachIt is worth to mention here that this is quite in contrast to other attempts like the so-called "relativized" quark models GoIs85,CaIs86 which just parameterize relativistic effects and therefore introduce additional parameters. To be specific, we now have to fill in the details of the underlying quark interactions, *i.e.* we have to specify the three- and two-body potentials $V^{(3)}$ and $V^{(2)}$, respectively, which we use as instantaneous interaction kernels. We then solve the resulting Salpeter equation numerically. The fact that this equation can be cast in Hamiltonian form allows for the use of a variational principle: We expand our wave functions in terms of harmonic oscillator functions and diagonalize the Hamiltonian with respect to a truncated wave function basis checking carefully numerical stabilities.

One of our aims is to extend a covariant quark model for mesons ReMu94,MuRe94,MuRe95,Mu96,MePe96,RiKo00,KoRi0 which is based on the quark-antiquark Bethe-Salpeter equation with instantaneous two-body interaction kernels. In this model the interaction between quark and antiquark included a linearly rising (string-like) confinement potential provided with a suitable spinorial form (Dirac structure), which was combined with the effective residual interaction first computed by 't Hooft from instanton effects in QCD tHo76. In fact it turned out that this relativistic approach, which employs 't Hooft's force as residual interaction, provides significant improvements with respect to other, non-relativistic or "relativized" approaches which in general use parts of the residual one-gluon-exchange in addition to a confining central potential. In particular, this model allows for a consistent and complete description of the whole mesonic mass spectrum but at the same time also for the description of dynamical observables such as form factors, where a fully covariant treatment of the quark dynamics becomes particularly crucial. The results are rather encouraging to extend this

ditional parameters. .

approach to baryons. Thus, our main choice for $V^{(2)}$ is 't Hooft's instanton-induced quark interaction. However, in appendix sec:OGE we will also show the result of calculations with a one-gluon-exchange potential, demonstrating that from a phenomenological point of view it should be discarded.

Similar to the Salpeter model for mesons, quarks in baryons shall be confined by a linearly rising string potential. Generalizing the linear quark-antiquark confinement for mesons our quark confinement for baryons will be produced by a three-quark string potential $V^{(3)}$ provided with an appropriate Dirac structure. As in the meson model ReMu94,MuRe94,RiKo00,KoRi00 we use in addition 't Hooft's two-quark interaction mentioned before as residual two-body force $V^{(2)}$. A non-relativistic version with these dynamics has been applied already by Blask *et al.* BBHMP90,Bl90,Met93 for the calculation of baryon (and meson) mass spectra. We would like to note that this model could satisfactorily account for the gross features of the light baryon spectrum with only seven parameters. In particular, it was able to explain the sign and the rough size of hyperfine splittings of ground-state baryons as well as the right size of splittings of negative parity excited baryons. However, a closer look at the mass spectra reveals that special features, such as *e.g.* the conspicuously low-lying first scalar/isoscalar excitations of the octet ground-states (Roper resonances) or the highest members of Regge trajectories cannot be accounted for in the non-relativistic framework. In particular, these issues improve in the present relativistic approach. We will not always comment in detail on calculations in alternative baryon models; for an excellent review see ref. CaRo00.

In this paper baryon resonances are treated as bound states and no calculation of widths is performed. This is certainly questionable, but so far is due to technical limitations. To improve this situation one has to specify the decay channels and perform at least a perturbative calculation of the decay widths Ma55. Very often this is not sufficient since final state interactions may also change (nonperturbatively) the resonance positions appreciably An97,An98a,An98b,AnSa97,AnSa96,AnProSa96. As long as this shift is approximately uniform, it can be absorbed in the potential parameters of the quark model. We are aware of the fact that this is true in many, but not all cases An97,An98a,An98b,AnSa97,AnSa96,AnProSa96.

Our paper is organized as follows: In section sec:3bodyConf we specify the explicit form of the instantaneous three-quark confinement kernel $V^{(3)}$. We introduce two alternative confinement models (model $\mathcal{A}$ and model $\mathcal{B}$) which essentially differ in the choice of the Dirac structures only. Both versions shall be tested in the subsequent investigations in a comparison to the experimental mass spectrum. In section sec:eff$_t$*HoLagweintroduce't Hooft'sinstanton−inducedresidualtwo−quarkinteractionanddiscussitsspecificstructure.Inth*
strangebaryon(andground−state)spectrumisgiven.Westartwithsomegeneralcommentsconcerningtheparameterdependenc
spectrum where 't Hooft's interaction gives no contribution. These investigations constitute a first test of the confinement models considered. Section sec:ground$_h$*yperisconcernedwiththehyperfinestructureoftheground−*
statebaryonsandtheroleoftheinstanton−inducedinteractionforgeneratingthisstructure.Sectionsec : Nucisdevotedtoanext
inducedeffectsalongwiththe$\Delta - N$ hyperfine splitting simultaneously generate several prominent structures seen in the experimental nucleon spectrum such as *e.g.* the low position of the Roper resonance or the occurrence of approximate "parity doublets". Finally we give a summary and a conclusion in section sec:concl. A detailed discussion of the corresponding results for the strange baryons will be presented in a subsequent paper Loe01c.

Three-body confinement sec:3bodyConf It is well known that the global structure of the experimental baryon and meson mass spectrum suggests a linearly rising, flavor-independent confinement potential. The appearance of the experimentally observed baryon resonances as nearly degenerate, alternating even- and odd-parity shells motivates the picture that the quarks are moving in a local potential which roughly reflects harmonic forces between the quarks. This picture led to the naive quark oscillator shell model. Moreover, phenomenological analyses of the experimental baryon (and also meson) spectra up to highest orbital excitations show a remarkable empirical connection between the total spin J and the squared mass M^2 of the states, namely that certain states, within a so-called Chew-Frautschi plot of M^2 *versus* J, lie on linear Regge trajectories $M^2 \sim J$. The interpretation of this empirical feature motivates a string picture for the confinement mechanism, where the quarks are connected by gluonic strings (flux tubes) such that the effective confining potential rises linearly with the string length for large distances of the quarks. A further confirmation of this scenario stems from lattice QCD calculations, which in fact indicate a string-like realization of the confinement force in the static limit of heavy quarks; for a review of these issues we refer to Bal00 and references therein.

As illustrated in fig. fig:3QConf there are several possibilities to define the linear inter-quark distance, which we refer to as Y-type, Δ-type and hyperspherical (H) string. figure[!h] center file=3QConf.eps,width=160mm